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The Photometry of Projected Light

By J. M. WALDRAM, B.Sc., F.Inst.P. (*Fellow*)

Summary

The paper discusses the problems of measurement of the performance of projection equipment such as that used for signals, beacons and search-lights, and the methods and equipment used for various classes of projector in laboratories in different countries.

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(6) DETERMINATION OF BEAM FLUX.

APPENDIX: Distance of Crossover Point for Projection Equipment.

(1) Introduction: The Required Accuracy of Measurement

A discussion of methods of measurement of the properties of a piece of equipment must begin by considering the precision required of the results, which leads to consideration of the purpose of the equipment, the tolerance permitted in its performance, and the relationship between the performance and the property measured.

Projection equipment used, for example, in aviation lighting is used either to provide a signal light visible to the eye (beacons, signals, runway marker or taxi lights) or, less frequently, to render objects visible (aircraft landing lights, floodlights). The range at which the light or target will be visible just conspicuously enough for the purpose of safe navigation is usually the criterion of performance, and the ranges are nearly always long. The limiting conditions, in which the equipment can function, are usually determined by the transmission of the atmosphere.

It is characteristic of the eye that it is not possible to determine with great precision

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NOTE: This communication was prepared in 1948 as Part 6 of a compendium which is being sponsored by the American Illuminating Engineering Society. This is the first part to be published. The plan is to publish other parts and chapters as they are completed either as technical papers or as separate publications of the I.E.S. in New York. It is hoped that the collected parts will be ultimately available under the title "Elements of Signal Lighting."

the conditions in which a given light is just not conspicuous enough, or at which the ground, for example, is just not sufficiently clearly revealed. The range at which it is required to see a light cannot even be specified precisely, and is often arrived at by estimates which in the nature of things cannot be exact. In the weather conditions in which the limit of safety of the lighting system is being approached, the range is determined mainly by atmospheric conditions, and may vary rapidly with changes in the atmosphere which are themselves considerable, indeterminate and out of control. In such circumstances changes in light intensity have a comparatively small effect on the limiting range. In clear weather, when the light intensity has a greater effect upon the limiting range, the latter is often so great that it ceases to be of interest.

For example, consider a night when the meteorological visibility range is 1,000 yards and a light is required to be visible at 2,000 yards. If a threshold eye illumination of 0.5 mile candela is assumed for design purposes, the necessary intensity for white light at night is 1,300 candelas. But if the range required is increased by 10 per cent. to 2,200 yards, the intensity required is 3,000 candelas, which is more than double the former value. If the visibility improves a little to give a meteorological visibility range of 1,200 yards instead of 1,000, the necessary intensity becomes 350 candelas. These figures are based upon a value often assumed for design purposes for the practical limit of signal lights, viz., 0.5 mile candela. Various authorities, however, have estimated that the practical limit is between 0.26 and 0.78 mile candela, which, for a required range of 2,000 yards and visibility range of 1,000 yards, would make the necessary intensities between 675 and 2,030 candelas. Military applications in which a light must certainly not be seen at some given range might involve the extrafoveal threshold which is variously estimated from 0.002 to 0.029 mile-candela, and which might be interpreted as meaning that a light of 5.2 candelas might just be seen occasionally in the above conditions. When the projector is intended to make non-luminous objects visible at a distance, the required intensity is still more variable because, among other factors, the range through the atmosphere is increased and because the varying properties of the target are involved.

It is also necessary to estimate the precision to which an intensity needs to be determined by experiment in view of the precision with which it will be reproduced in practice. The intensity from a narrow beam projector in a given direction will depend markedly upon the position of the lamp in the optical system, and upon the setting of the optical system in the projector, as well as on the training of the projector as a whole. When a number of projectors is in question, as for a system of approach and contact lights, it is necessary further to consider the variation from one projector to another of both the optical systems and the lamps, and their settings, in combination, as well as the tolerances to be expected in training individual projectors. The whole problem, if considered formally, would involve a considerable statistical analysis upon the data for a given piece of equipment, which is seldom available in the required form; for the moment it is sufficient to observe that there is little point in using refined procedure to determine the luminous intensity of a projector correctly to 5 per cent., if the changing of a lamp or reflector for a spare is likely to change the intensity by 20 or 30 per cent. and when a change of 2:1 can occur before the working range is significantly altered. Notwithstanding these arguments, it is important to take the usual photometric precautions, to use accepted technique and to avoid systematic errors. The special difficulties attendant upon long range photometry are often sufficient to reduce the accuracy to $\pm$15—20 per cent.* even when all reasonable precautions have been taken; if they are not taken, the measurements may go out of control. Nevertheless, the problem of the photometry of projectors lies as much in

* Rey and Févrot (19) estimate, for axial measurements on carbon arc searchlights under very good conditions, a probable error of 10 per cent. Winch (21) quotes a similar accuracy. These accuracies are obtained only with great care.

the study of the projector itself, its optics and its proper adjustment, as in the measurement of its intensity, and the interpretation of the results is not always straightforward.

(1.1) The Meaning of Luminous Intensity

The purpose of most projectors reduces in practice to the provision of illumination at a distance, whether the projector is intended specifically for this purpose or for the production of a signal light. Even when there is no real surface to illuminate and the light is to be looked at directly, it is, nevertheless, the illumination on a fictitious surface at the observer's eyes which determines whether or not he will see the light.

If a series of measurements of illumination is made at increasing distances from a light source, it is found that in the absence of atmospheric scatter or absorption, the illumination is related to the distance by the law of inverse squares, to a degree of approximation which improves as the distance increases. If then the illumination is measured at some known distance at which this law applies sufficiently closely, then the illumination at any still greater distance can be found by calculation. It is then convenient to determine the luminous intensity, as a useful simplification. But the quantity known as luminous intensity is useful only as a step in a calculation which is valid only in certain defined conditions, and if those conditions do not apply, "luminous intensity" has no meaning, and the calculation is invalid. Projection equipment is occasionally used at distances at which the inverse square law does not apply; in such circumstances it cannot be said to possess "luminous intensity," and performance must be measured by direct illumination measurements at the working range. It is thus important to know in any given case the least distance at which it is justifiable to assume the inverse square law, and the least distance at which photometric measurements can be made from which performance can be estimated at greater distances with an accuracy *sufficient for the purpose in hand.* This latter phrase is important, for if a reasonably large tolerance is permissible in the determination of luminous intensity, it may be possible to take certain photometric liberties—provided their effects can be estimated—and greatly simplify the experiment, without prejudicing the final result in terms of operational range in some stated conditions.

(1.2) Limitations of the Inverse Square Law: Ideal Optical Systems

To determine the limitations of the inverse square law it is convenient to consider a point at the receptor which receives light from a projector or light source of finite subtense.

(i) Consider first a light-source in which every point of the source has the same luminance in all directions, such as a large opal sphere with a lamp in it. If the receptor approaches the light source, departures from the inverse square law will occur because the angle of incidence on the receptor of the light from the margins of the source reduces, by operation of the cosine law, the illumination which it produces. A significant error occurs, for a disc source, only when the receptor is quite close to the source; the error is 5 per cent. when the receptor is distant four and a half times the diameter of the source. (7).

(ii) A variant of this occurs when the luminance of the source is not uniform from point to point of the source, but when at any one point the luminance is the same at all relevant directions of view; an example would be an opal globe not uniformly bright, or a bare lamp. The distance at which a given error occurs may be of the same order as in the first example; its value depends upon the kind and degree of non-uniformity of luminance over the source.

(iii) A more complex example, which is usual with projectors, occurs when the luminance at any point of the projector aperture, as seen from directions near that of the receptor, varies markedly with direction of view. If then the receptor is too

near the projector, the luminance of some parts of the latter may differ from their value for a receptor at a great distance, because those parts are viewed from a slightly different direction, and the determination of the least permissible photometric distance involves a study of the projector itself in some detail.

For this purpose it is convenient to trace rays back from a point at the receptor through various parts of the projector. After reflection or refraction at the optical system, some such rays will arrive at a bright part of the light source; the corresponding parts of the aperture of the projector will therefore appear bright. With a perfect optical system (designed to give light parallel to the axis) and a finite and uniformly bright source at the focus, for points near the axis at a great distance the whole projector aperture will appear bright; the projector is then said to exhibit "complete flash" and its luminous intensity is maximum for the luminance of the source used. If the luminance of the source is uniform, as the receptor approaches the projector the flash will still appear to be complete so long as all rays traced from the receptor to the margin of the optic pass after reflection or refraction through some part of the source. The correct luminous intensity will be measured, unless the source is very large, so that the distance can be reduced to the point at which the angle of incidence of light from the margins is excessive, as in the first example. When rays from some part of the projector aperture fail to reach the source, the flash will be incomplete and the intensity measured will be low. For a perfect optical system and an idealised light source, such as a disc, line or sphere, centred upon its focus, it is possible to calculate the "crossover point," i.e., the point at which the marginal rays of greatest deviation reach the axis. This is the least distance at which the full-flash luminous intensity can be measured for a source centred upon the focus. Formulae are given by various authorities ([1, 2, 6, 11, 19]). (See Appendix.)

For directions of view well off the axis it is inevitable that only a partial flash will occur and the conditions become more complex. It is again possible to compute (for a perfect optic and idealised source) the least distance of measurement at which no theoretical error occurs, which is usually greater than when viewing close to the axis. Sometimes the distance becomes infinite—a result which demonstrates that such estimates are rather academic. Walsh ([2]) has shown that the error resulting from a reasonable transgression of the theoretical limit is negligible (see below).

(1.3) Limitations of the Inverse Square Law: Practical Optical Systems

These theoretical conclusions have to be modified in practice. Optics are never perfect, and often have least circles of confusion comparable in size with that of the source employed; sources are far removed from the ideal sphere or disc assumed in the calculation and are very seldom of uniform luminance. As a result, a ray traced back through a point on the projector aperture does not arrive at a determinate point on a uniform disc or sphere source, but may arrive anywhere over the surface of a source whose luminance is very variable, or may miss it entirely. Even for a receptor beyond the theoretical "crossover point" for a perfect optic, therefore, the flash may be incomplete, or although apparently complete, various parts may have different luminance as a result of the errors in the optic and the variations in luminance over the source. In practice, therefore, the calculation of the "crossover point" may have a restricted significance.

There is also the problem of the adjustment of the projector. Unless the focus is fixed, it becomes necessary to adjust the source relatively to the optic and to train the whole projector in order to find the maximum intensity and to explore the light distribution of the beam. The focusing must be carried out on the photometric range at a distance less than infinity, and with imperfect mirrors and non-uniform sources it is practicable only to adjust the projector for the range used. The question

of what would have happened had the projector been adjusted for best focus at infinity often becomes academic.

It will be seen, however, that if the projector is adjusted to give the optimum result at the distance at which it is being tested (provided that the optical system permits and validates such adjustment) the conditions become very nearly the same as those for a receptor at infinity and a source centred upon the focus, even if the source is non-uniform and the optical system has appreciable errors of figure. If this can be done, it is possible to make measurements with adequate accuracy at distances well within the "crossover point." It is, however, difficult to lay down precise rules for the safe photometric distance for a given error, for the extent to which liberties can be taken depends upon the projector and the required accuracy.

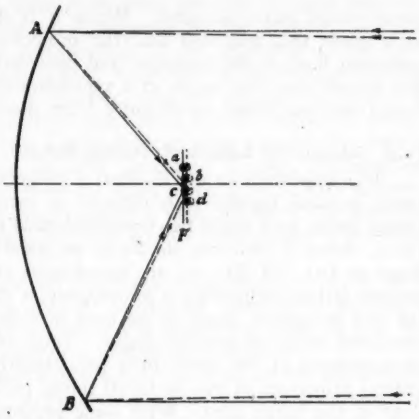

Fig. 1. Effect of focusing for testing range.

For example, in Fig. 1 consider a parabolic mirror of imperfect figure, having a large filament lamp with the filament centred closely about the focus. The filament has four coils at *a, b, c,* and *d*. Suppose that the position of the filament shown gives the highest intensity for a receptor at infinity. Rays traced back from such a receptor through two points A and B on the mirror are shown by solid lines. Owing to slight imperfection in figure the ray reflected at A crosses the axis just behind the focus, and that reflected at B crosses just in front of it, and they both strike coil *c* of the filament. From a very distant receptor, therefore, A and B are both flashed by coil *c*. If the receptor is advanced closer to the projector, rays from the receptor to A and B are now no longer parallel to the axis and might follow the path shown by the dotted lines. After reflection they cross the axis further from the pole of the mirror, and both go through gaps in the filament structure, that from A going between limbs *b* and *c*, and that from B between *c* and *d*. From the nearer receptor, therefore, points A and B will no longer be flashed; the flash pattern will have changed. But if the lamp is moved out through the small distance shown by the dotted line, it will be seen that the original condition is restored, and the rays after reflection strike the same limb of the filament in the same point.

Winch and his collaborators ([21]) investigated a 156-cm. searchlight and a 150-amp H.C.D. arc, the central portion of the arc, which was of approximately uniform luminance, having a diameter of about 3 mm. The theoretical "crossover point" for non-axial measurements was then calculated to be about 4,000 ft. for a 3-mm. disc source and about half that distance for a spherical source, the arc being somewhere between the two. Careful measurements were made of the cross section of light distribution at 1,500 ft. and 5,000 ft., the projector being focused to give optimum flash for each distance in turn. It was found that *provided that the projector was so focused,* the results either on or off the axis for the two distances were indistinguishable within the errors of measurement. This was confirmed theoretically for sources as small as 2 mm. in a 156-cm. dia., 65-cm. focus paraboloid. This means that for the shorter range the light source was not centred on the true focus of the mirror, but the displacement, being of the order of 2 mm. only, was of no consequence. Had the arc been set by the focuscope to the measured focus of the mirror, a perceptible

error would have occurred. While it is difficult to dogmatise, it might be taken as a guide that provided that the projector is focused for maximum intensity and optimum flash at the receptor, and provided that the change in lamp position which this entails does not result in a significant change in beam divergence, the intensities found will not differ significantly from those found at greater ranges.

(1.4) Selection of Length of Testing Range

It is important to use as short a range as possible, for the difficulties of measurement increase rapidly with increase in range and the theoretical advantages of the longer range may easily be counterbalanced by the greater uncertainty of measurement there. Since it has been shown to be possible to photometer accurately projectors as large as 150 and 200 cm. arc searchlights at 1,500 ft., and since such ranges do not present serious difficulties in photometry, it should be unnecessary to use longer ranges for any projectors likely to be used in aviation problems; smaller projectors can be measured safely at smaller ranges. Thus, even very critical projectors may be safely photometered at 700 times their focal length and probably less, and smaller and less critical projectors at say 30 to 50 times, provided that they are focused for optimum flash at the range used. With some projectors, however, it may be impracticable to adjust the focusing of the lamp for the distance of measurement. An example is optics of the lighthouse type, in which the optical system rotates about a central lamp, and where both dioptric and catadioptric elements are used. One element requires that to correct for the testing range, the lamp should be moved away from the optic, and the other that it should be moved towards it. In optical systems of this type the theoretical "crossover point" may form a guide to the least safe distance of photometry. It is also necessary to allow for chromatic aberrations when testing dioptric projectors of critical performance [6, 11].

(2) Problems of Photometry of Projectors over Long Range

The determination of the luminous intensity of a projector over a long range necessitates (i) the adjustment of the projector to the desired performance; (ii) the training of the projector into known directions relative to the receptor; (iii) the determination of the luminous intensity, either from the illumination received at a known distance, or by comparison with that of a known projector. It is usual to determine the luminous intensity as in perfectly transparent air, so that allowance for atmospheric transmission can be made when the data are used; this may involve in addition the determination of the atmospheric transmission over the photometric range when the luminous intensity is measured. Methods for carrying out these operations will be described, mainly with reference to long testing ranges; simplifications possible at shorter ranges will be obvious. It is not proposed to discuss techniques and apparatus which are common to any photometric experiment; what follows is confined to the special problems of photometry of projectors.

(2.1) Focusing and Adjustment of Projector

In most projectors it is possible to adjust the light source in position relatively to the optical system, and before commencing photometry it is necessary to adjust the projector.

Many projectors used in aviation will be designed for maximum concentration of light and complete flash, relying on the size of the light source and possibly a spreader glass to produce the required divergence of the beam. If a spreader glass is used, it can be removed and the projector set to maximum intensity. Some projectors are provided with sights whereby the lamp can be set at the focus of the optical system, which should be correct if the projector is to be set for infinity. It is, however, always

desirable to check that such sights have themselves been properly set and that the projector is giving its optimum performance. It is desirable for the reasons discussed in Section (1.3) to adjust for the optimum performance for the test range rather than for infinity. This can be checked for complete-flash projectors by adjusting either for optimum flash, or for maximum intensity; in practice, both criteria may be used. A study of the flash is most useful for preliminary adjustment and to reveal the causes of departures from expected performance; it is a good guide to what is happening during adjustment. For the final stages, a more sensitive indication is often obtained by setting to the maximum luminous intensity. For the study of the flash, a flash camera, described in Section (3.2) is invaluable; it should enable a large image of the aperture of the projector to be studied at the receptor, and may enable photographs of the flash to be made for record and study.

Projectors which are not complete-flash, but which are designed with a partial-flash reflecting or refracting scheme to give a desired distribution, cannot be so simply adjusted, but if the intention of the design is known it is possible to study it with the aid of the flash camera and to check whether it is performing properly.

The use of a flash camera in conjunction with a special artificial source also enables a study of errors of optical systems to be completely explored([21]), but this investigation goes beyond the photometry of projected light.

The optical axis of an optic such as a good paraboloidal mirror can be determined by stretching two elastic cords across the front aperture so that each bisects the other, using their intersection and the image of their intersection to determine the axis; the lamp can be set upon this axis. This assumes that the mirror axis coincides with the mechanical axis. Many mirrors have the position of their pole marked on the mirror itself; the lamp can then be set so that the filament, the pole mark and the image of the filament are colinear ([23]).

A method for focusing and alignment of carbon arc searchlights, which sets the projector for the photometric distance and may be practicable where other methods are not, is used in some laboratories ([23]). A hollow sighting tube with pin holes at both ends is substituted for the positive carbon, and the searchlight aligned so that the tube is directed at the photometer. A small white card is then pasted to the end of the tube at the location of the positive crater. If the reflector is in approximate focus and alignment, an image of the photometer will be visible on the card. If this image is centered on the card, symmetrically distorted, and brought into optimum focus, the searchlight is both aligned and focused for the photometric range.

To determine the amount of obstruction due to lampholders, focuscopes, ventilating trunks, etc., a small tungsten filament lamp may be placed at the focus and a sheet of translucent paper placed over the front aperture. The shadows of obstructions then appear on the paper and can be traced in pencil ([19]).

(2.2) Training of Projector

It is necessary to train the projector through small known angles in both elevation and azimuth so that the light distribution can be fully explored over the whole beam. When the beam is narrow this involves taking observations at intervals of, say, 0.1 deg., and for projectors without suitable mountings it is necessary to provide an accurate and rigid turntable, with the necessary slow-motions and scales. Some designs of turntable are described in Section (3.1) below. For very large projectors, or projectors which cannot conveniently be rotated, the receptor may be moved about the projector ([27]); this may be convenient for field tests, but is a cumbrous undertaking for a permanent range. Angles are obtained very accurately, but weathering and change of temperature introduce difficulties. In field tests, particularly upon projectors with fan beams such as aerodrome floodlights, it is important to survey the site for change in level and to correct accordingly ([11]).

(2.3) Procedure in Determining Luminous Intensity

The luminous intensity can be determined in one of two ways: (i) as the absolute illumination received at a known distance, corrected for atmospheric transmission; (ii) from the ratio of the illumination received from the test projector to that received from a standard projector whose intensity is known.

The first method has advantages for field tests, and may be called for when no standard projector is available. Its advantages and disadvantages are set out in Table I.

Table I

Measured Illumination Method

Advantages	*Disadvantages*
Avoids use of standard projector, and its calibration, power supply, etc.	Not a substitution method.
More flexible for field work.	Atmospheric transmission must be separately determined; this requires telephotometer and light source, or equivalent, as well as illuminometer: usually possible only at night.
Calibration procedure simpler.	Length of range must be accurately known.
	Photometric scale resides in illuminometer.
	Cannot frequently refer to standard.

The second and preferred method, using a standard projector, is a pure substitution method with its usual advantages; the atmospheric transmission is automatically allowed for, and the length of the range does not enter. There is, however, the difficulty of calibrating and checking the standard projector, which may be quite troublesome, though with sensitive equipment it is possible to refer the calibration back to a standard lamp which can be calibrated on a bench in the photometric laboratory. This method is better suited to established ranges than to field tests. The advantages and disadvantages are set out in Table II.

Table II

Standard Projector Method

Advantages	*Disadvantages*
Independent of atmospheric transmission and length of range.	Need for standard projector and supply (need to calibrate and check standard projector, if standard lamp cannot be used)
Absolute calibration resides in standard projector, or lamp; frequent reference to standard possible.	Less suited for field work.
Quicker than illumination method.	
Can be used in daylight, with adequate shielding.	

It is assumed that usual photometric procedure will be followed for maintaining constant voltage upon lamps, using lamps of known light output and correcting the results to the published light output at rated volts, etc. If lamps are underrun to ensure stable light output, they should not be underrun so far as to disturb the normal luminance distribution of the filament. This might occur with heavy-current low-voltage lamps in which the filament is short and in which there is considerable end cooling. Underrunning by 10 per cent. in voltage is usually sufficient and safe.

It is necessary to check zero readings, stray light, etc., and to make the necessary corrections, and it is wise to refer frequently to the standard projector. The programme of observations should be such that errors due to variation in transmission, stray light or sensitivity will be detected and eliminated as far as possible. Measurements should not be made when either the transmission is very variable or the daylight is rapidly changing (unless the stray light correction is negligible), or when "heat shimmer" is excessive. If the projector being measured subtends a small angle at the receptor, as is almost always the case, changes in refractive index of the atmosphere may cause fluctuations in the illumination of the receptor; and if the response of the receptor is rapid the readings will be unsteady, and false peaks and depressions may be introduced into the measured distribution curve.

(2.4) Determination of Atmospheric Transmission

Over ranges exceeding a few hundred feet it is necessary to make allowances for atmospheric attenuation, or to exclude its effect by the procedure used. The latter scheme is the more satisfactory; the pure substitution method, using a standard projector, achieves this result. If this is impracticable, the transmission must be determined over the full testing range. Even with the pure substitution method, trouble may occur from variations in atmospheric transmission during the experiment, which may be sufficiently rapid to upset the results.

The transmission varies exponentially with the range used, and its determination is a major problem at long ranges; as the range increases not only does the transmission fall rapidly but it becomes much more unsteady. Mainly for this reason it is desirable to keep the testing range as short as possible. The chart of Fig. 2 ([16]) is useful as an indication of the manner in which transmission changes with range, and also of the transmission to be expected in various conditions of daylight visibility. The curved lines relate transmission to range for a given scattering coefficient, the value of the coefficient being marked against the lines. The corresponding descriptions as used in the meteorological service are also appended. The meteoro-

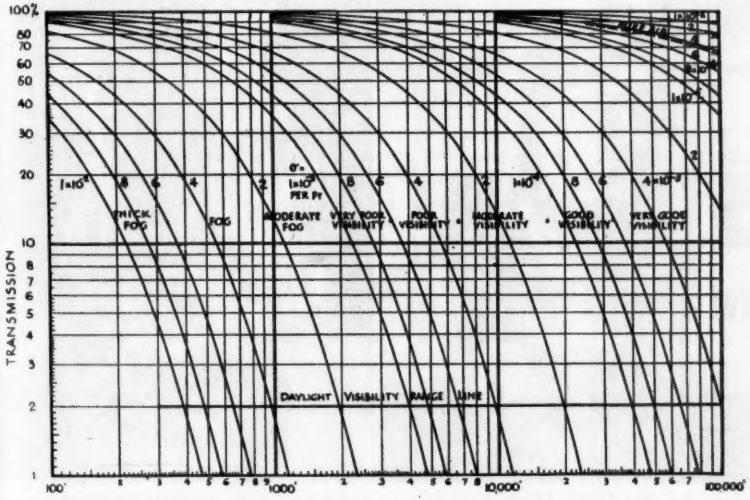

Fig. 2. Transmission, Range and Scattering Coefficient.

logical visibility range is given by the intersection of one of the curves with the line marked "daylight visual range line," for the transmission of the atmosphere at the daylight visual range can be taken as about 2 per cent. The transmission for any shorter range can be read from the chart by following up the corresponding curved line until it intersects the vertical line corresponding to the range concerned. For example, on a day of "moderate visibility" when the daylight visual range is 20,000 ft. (approximately four miles) the transmssion over a testing range of 1,000 ft. would be about 81 per cent.; on a 100-ft. range it would be almost 100 per cent., and on a 5,000-ft. range about 37 per cent. These figures are given for illustration only, and would not be reliable for corrections in an experiment, as they assume a uniform atmosphere.

The difficulties of measuring atmospheric transmission also vary with the range. At short ranges and in clear weather the transmission is high and needs to be determined accurately only if it is desired to extrapolate to find the transmission at a greater range—a procedure which is not to be recommended. When measured over the testing range, the necessary accuracy of measurement corresponds to that of the photometric accuracy required, but at long ranges the optical magnification involved is often inconvenient.

Two general methods are available: the measurement of the apparent intensity of a light source of known and fixed intensity, and the measurement of the apparent luminance of an illuminated screen of known luminance. The former method has two variants: the use of visual photometers of the stellar or Maxwellian view type, viewing the light source directly, or the measurement of the illumination from the source, using a receptor similar in principle to that used for the photometry of the projector. The apparatus involved will be discussed in Section (3.5). In this scheme it is necessary to know the range accurately. The second method is simpler in operation and the photometry is easier when visual photometry is used. The luminance of the illuminated

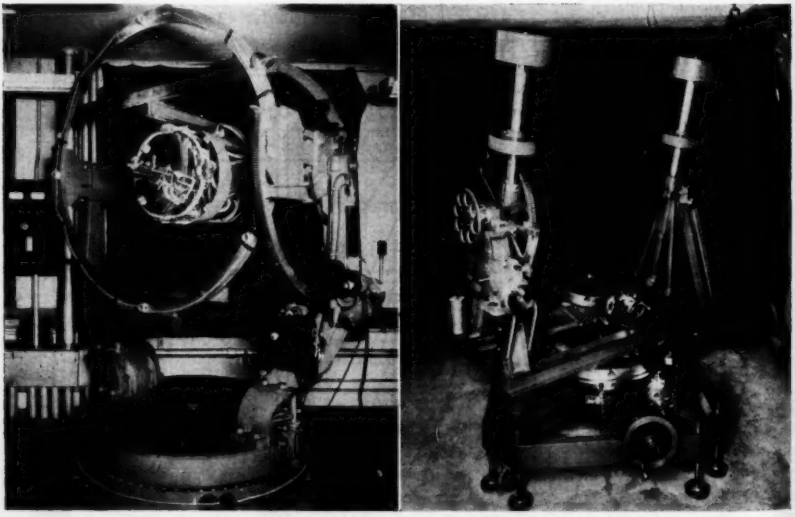

Fig. 3(a). *(Left).* Turntable and Goniometer based upon searchlight mounting.
Fig. 3(b). Turntable and Goniometer based upon dividing tables.

surface at the distant station must be accurately known, but the range does not enter in the determination of transmission. A portable visual photometer can be used to determine the distant screen luminance and also to determine the luminance of a local screen by which the telephotometer can be calibrated. At long ranges, however, the dimensions of the screen and of the optical system become inconveniently large, and the determination by this method becomes a formidable undertaking.

Other methods have been used. Hampton [11] determines the apparent intensity of the test projector at a number of distances; the logarithm of the apparent intensity plotted against distance should give a straight line which, when extrapolated to zero distance, gives the true intensity without atmospheric effects. Harcombe [3, 4] employs a two-station method with receptors at different distances; from measurements at the two distances the atmospheric transmission can be eliminated. These methods have disadvantages; they involve making some measurements at distances greater than necessary; they take longer; they assume a uniform atmosphere, which cannot be relied upon; and they require that the training of the projector should be precisely the same for each station. With some light distributions the training is not critical, but with narrow distributions it is difficult to ensure that the intensity presented to each receptor is, in fact, the same.

Other methods of estimating the atmospheric transmission include observation of the daylight visual range, mentioned above, and nephelometric methods [16]. Except where they indicate that correction for atmospheric transmission can be neglected they are to be avoided, for they are less accurate and do not measure the transmission over the testing range.

(3) Special Apparatus Required for Photometry over Long Ranges

(3.1) Turntable and Goniometer

Most laboratories design turntables appropriate to their own work; a searchlight mounting often forms the basis (Fig. 3a) [15, 23, 25, 26]. The usual requirement is a flat rigid table to which the apparatus can be attached, which is capable of rotation in azimuth and of tilting in elevation; for many purposes restricted angular ranges are sufficient. The movements must be accurate and rigid, and the table suitable for heavy projectors. In some turntables the platform is adjustable in height [25]. A slow-motion is very desirable, which can be disconnected for convenience in setting up.

T.H. projector describes (private communication) a goniometer [23], having an additional axis of rotation so that measurements can be based upon either a vertical or a horizontal polar axis (Fig. 3b). This goniometer is constructed so that two of the rotations are obtained with rotary dividing tables of the type used in machine shops. A constant torque device, visible in the figure, ensures the taking up of backlash after the inner frame is balanced with the adjustable counterweights.

For making a temporary turntable to take a heavy projector, the azimuth bearing has been formed by a spider carrying three ball-bearing wheels set at the extremities of three arms at 120 deg. These wheels run on metal plates laid on the floor, and the base of the turntable structure rests upon them with similar bearing plates. A restricted vertical movement was obtained with an automobile jack. This arrangement will carry a heavy load, runs very easily, and requires no centring bearing; it can be moved by a tangent push-screw [31] (Fig. 4).

Angular readings can be taken upon fixed circles, with verniers or from the slow-motion gearing, if this is sufficiently accurate and free from backlash. Readings may often have to be taken at intervals of 0.1 deg., which indicates the precision and rigidity required in the turntable and index. One turntable [26] has an index with two pointers geared like the hands of a clock for convenience in fine reading. For narrow-angle projectors a covenient arrangement is a telescope mounted on the turntable

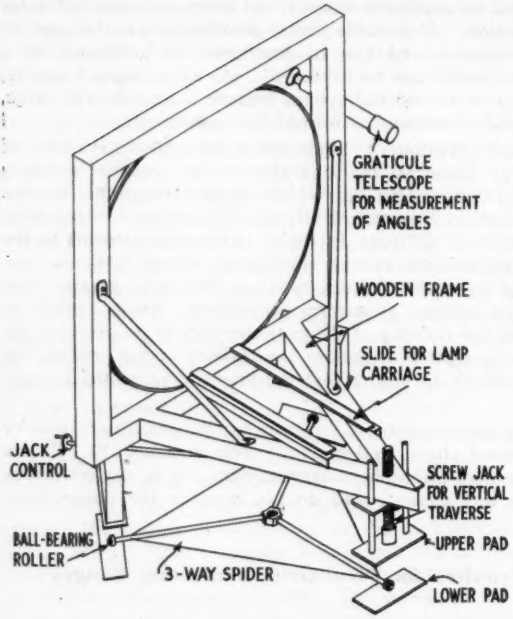

Fig. 4. Temporary turntable for optical system of large projector. (For clarity frame is shown raised from spider and lower pads.)

or on the projector itself, observing a grid showing angles in bearing and elevation ([28]), or, for smaller apparatus, a small projector imaging an index mark upon such a grid ([25]). For very narrow angle work, the telescope may carry a graticule graduated suitably, and the image of the receptor is read against the graticule ([31]). These methods avoid the need for accurate circles and centres, are conveniently set to zero and may be applied to projectors such as searchlights having their own trunnions.

Where automatic recording is used, the motion of the turntable is transmitted electrically to the recorder, either by a step-by-step motor ([29]), or by a periodic contact made by a commutator on the slow-motion shaft, or by the use of two synchronous motors connected to the same power supply ([23]). Fig. 3b shows a motor drive for automatic traversing at uniform speeds, and the commutator for transmission of signals to the recorder ([23]).

(3.2) Flash Camera

The flash camera should be capable of forming an image about 2-3-in. diameter of the projector aperture with reasonably good definition. At most long ranges a simple lens will have to be of inconveniently long focus; a camera in the form of a projecting telescope, having a projection eyepiece, is a convenient form ([10]). It is also convenient if dark slides can be inserted in place of the ground glass focusing screen for taking photographs, and a shutter is also required. One design has used an objective of 3-in. diameter and 50-in. focus, with a projection eyepiece, on a range of 1,500 ft. Winch and his collaborators describe ([21]) more elaborate forms with objectives of 5-in. diameter and 47-in. focus; a reflex arrangement being used whereby the image can be observed up to the moment of exposing the negative. This is a convenience when fluctuating light sources are used. In another apparatus the flash camera is

combined with the receptor unit, and the image can be observed with an eyepiece or photographed, as desired (Fig. 5).

An ordinary telescope, with suitable dark glass, may of course be used [19] but is less convenient than the projecting telescope.

(3.3) Receptor Unit

The receptor unit can take many forms. The essential is a test plate or photocell, shielded from all light except that from the projector under test. Visual photometry can be used but it is inconvenient and slow; for setting up and watching the effects of a change of atmospheric transmission and for rapid work, a photoelectric apparatus is much to be preferred. When fluctuations occur either in the light source or in the atmosphere, rapidity in measurement makes for accuracy. For this reason, as well as for convenience in recording the detailed variation of intensity with angle, continuous recording has advantages and is strongly recommended by some establishments [23, 29].

Automatic recording can be made with a suitable oscillograph or recording galvanometer, preferably high-speed. In one establishment [23] a multi-element string oscillograph is used with galvanometers having sensitivities as high as 0.1 micro-amps. per mm. and suitable for direct connection to a photovoltaic cell. Photometric and electrical measurements and training of the projector are simultaneously recorded, the latter by contacts actuated by the slow-motion gear. This enables a curve to be obtained in two or three seconds. Automatic recording potentiometers can also be used; the high-speed types enable rapid photometry to be carried out. These elaborations, though convenient, are not essential for most work; a straightforward galvanometer with lamp and scale is adequate for medium ranges.

(3.3.1) *Shielding*

It is a great convenience to be able to make measurements by day, but it is difficult to shield the receptor so that it accepts light from the test projector and is shielded adequately from stray daylight. The test projector should be placed in a fairly large building of dark colour which will form a good back screen; preferably it should be placed within a dark room projecting its beam through an aperture, say, 6-10 ft. square, the aperture not being close to the skyline as seen from the receptor. If possible, the use of a range running east and west should be avoided, otherwise low sunlight may be troublesome. The line of sight should preferably be well clear of the

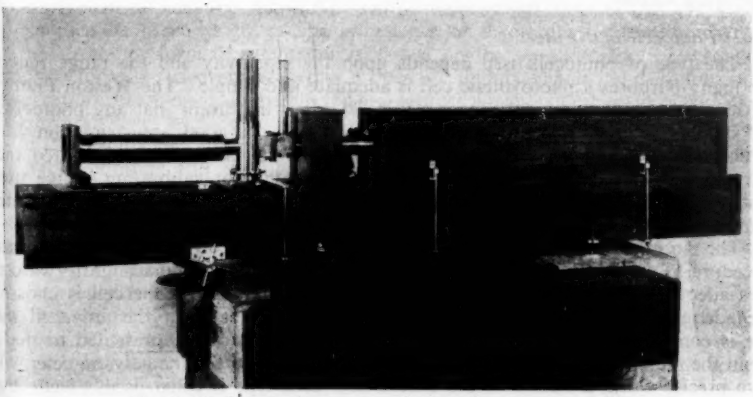

Fig. 5. Combined tele-camera and photoelectric receptor [31].

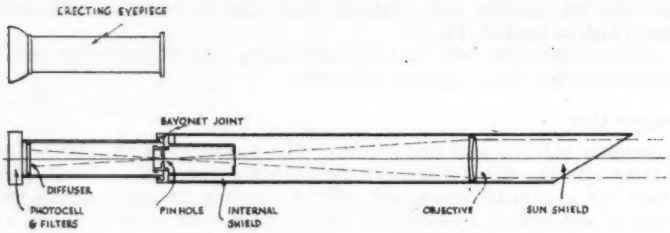

Fig. 6. Optical shield receptor unit. (Simple type; diagrammatic only.)

ground, to reduce light reflected from the ground (at night) and to avoid the layer of atmosphere close to the ground, which is most likely to be unsteady. Irregular terrain, and surfaces such as paved roads likely to be strongly heated by day should be avoided. Conventional photometric shielding may be used, the first series of shields being fitted within a long black tunnel, say, 8-10-in. diameter. Further large black shields can be used external to the tunnel and of such size and position that the receptor can see only the backs of the shields and the aperture through which the projector operates ([23]). With photocells of usual dimensions the shielding becomes rather cumbersome, and there is also possibility of stray light reflected from the backs of the external shields, which are exposed to full daylight and possibly sunlight, and which, being exposed to weather, it is difficult to maintain really black. Such shields should preferably be hooded to reduce their illumination.

A more compact arrangement (Fig. 6) utilises a form of telescope ([21]), in which the objective lens forms an image of the distant projector upon a small pinhole, just larger than the image of the projector, placed at the principal focus of the lens. The only light passing through the pinhole is light received from the projector; all other light is focused elsewhere and is stopped by the diaphragm. After passing the pinhole the light diverges and reaches a photocell, after passing through a diffuser. Such an arrangement requires to be rigidly mounted and to have adequate slow-motions for adjustment and an eyepiece by which the image of the projector can be centred on the pinhole; it is also necessary to shield the surface of the lens from direct sunlight, since a little light is always scattered at the lens. Difficulty may be experienced in hot weather over long ranges from "heat shimmer" due to rising currents of hot air of varying density.

(3.3.2) *Photocell and Filters*

The type of photocell used depends upon the sensitivity and the range required. For many purposes a photovoltaic cell is adequate and simple. The Weston Photronic cell has been used on several ranges ([23, 28, 29]). It is important that any photoelectric cell should be used in conjunction with filters giving a good approximation to the standard relative luminous efficiency curve, and that ultra-violet and infra-red radiation should be excluded, particularly when the standard or calibrating source uses a light source different from that in the test projector. When mercury-vapour or carbon arcs are used this is specially important.

The circuit used with photovoltaic cells should be in accord with usual photometric procedure. For most work a reflecting galvanometer is simple and straightforward and gives adequate accuracy, provided that the resistance burden on the cell is chosen to give adequate linearity of response. An electrical attenuator of the universal shunt type is convenient, as it can be arranged to keep the resistance presented to the cell within the required limits and still preserve critical damping for the galvanometer. For more precise work, a circuit of the Campbell-Freeth type is often used, of effectively zero resistance, which gives a more nearly linear calibration (Fig. 7) ([8, 12, 14]). The

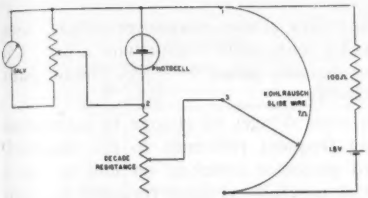

Fig. 7. Circuit for photovoltaic cell (14).

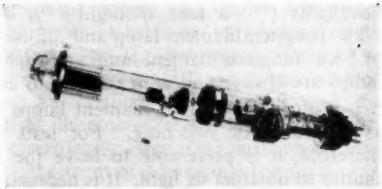

Fig. 8. Photometer unit (31).

linearity of the complete equipment of cell, attenuator and galvanometer should of course be checked. A commercial photoelectric illumination photometer may be used, with suitable filters; it should be checked for reliability, stability, and linearity of response (19).

Where greater sensitivity is desired, an electron-multiplier type of cell may be employed, using conventional circuits with accurately stabilised voltage supplies. This type of cell gives much greater sensitivity, but its stability needs to be watched.

Another type of instrument of high sensitivity and precise linearity uses a vacuum cell with a valve-bridge amplifier; the cell and electrometer triode valve and leak resistance are hermetically sealed into a single unit (9, 17) (Fig. 8). This apparatus, operating in conjunction with the optical shielding unit described above, is sufficiently sensitive to measure a 1,000-watt lamp at 1,500 ft. in daylight, though the correction for stray light is then a substantial fraction of the reading for the lamp. It is usually employed with a liquid filter of the Preston type giving a close approximation to the standard relative luminous efficiency curve.

It is possible to run a circuit from the receptor unit back to the projector, an arrangement which is very convenient since the measurements are all made at one end of the range, but it is necessary to guard against effects of capacity and of electrical leakage when very small currents are involved, particularly over long ranges.

(3.3.3) *Optical Attenuators.*

A receptor unit must operate over a large range of intensities in order to step from that of the calibrating source to the peak intensity of a powerful projector. It is desirable to use strictly neutral attenuators such as sector discs, and discs with transmissions down to 1 per cent. have been successfully used. At low transmissions, however, they require to be very well designed and made. In optically shielded receptors it is sometimes convenient to place the sector disc near to the principal focus of the lens; a small disc can then be used, which can be swung out of the way conveniently when not required. Another form of attenuator is a stop on the objective lens of the optical shield, which can be used provided that it does not unduly impair the definition of the image. Sector discs are inadmissible for a.c. sources which exhibit periodic flicker, for which neutral filters provide convenient attenuators. They should be calibrated with light of the colours concerned and with the receptor and colour filters used, particularly when the calibrating and test lights are of different spectral composition.

(3.4) Standard Projector

The requirements for a standard projector are:—

(i) A maximum intensity capable of providing an adequate response at the receptor.
(ii) A light distribution which is smooth and fairly broad so that the training of the projector is not critical.
(iii) An optical system which permits of calibration at fairly short range, so that it can be calibrated in a laboratory without the need for a long range.
(iv) A light source which is stable over long periods, and preferably unaffected by switching.

Various forms of standard projector have been used—e.g., a battery of sealed-beam

headlights ([23]); a lens spotlight ([30]); a modified film studio mirror projector, with 5-kw. tungsten filament lamp and diffuser ([31]); and a searchlight mirror with a 0.5-, 1.5- or 5-kw. tungsten filament lamp and slightly diffusing front glass ([28, 29, 31]). The tungsten lamps are always underrun suitably to ensure stability.

With heavy-current filament lamps there is some danger of change in calibration as the result of switching. For tests involving frequent reference to the standard, therefore, it is preferable to leave the standard projector switched on and to use a shutter to obstruct its light. It is necessary to check carefully at fairly frequent intervals the intensity of the standard, and the accuracy of alignment of the sight by which it is trained on the receptor. In one laboratory ([31]) an auxiliary indoor range was provided, by which the intensity of the standard could be checked, using a photometric bench at the other end. The standard projector could be trained from the calibrating to the test range without shifting its position.

If the receptor is sensitive enough, it may be possible to obtain sufficient response from a large bare tungsten filament lamp over the full range; the stray light in daylight is then rather large, but can be measured and subtracted if steady. Such a lamp can be calibrated on the bench in the usual way, and it then becomes possible, by the use of suitable attenuators, to step from a bare lamp giving 1.5×10^3 candelas to a standard projector giving 5×10^5 candelas and thence to test projectors giving 10^9 or 10^{10} candelas ([21]).

(3.5) Apparatus for Determination of Atmospheric Transmission

On permanent ranges when the substitution method is not employed, it is usual to employ a transmissometer in which the intensity of a calibrated light source or projector is measured by a photoelectric receptor. Douglas ([18]) has described a photoelectric electronic instrument for permanent installation. At another testing range ([29]) a second receptor with continuous recording is used to receive light from a standard projector to record relative transmission continuously during a test. A simple instrument has been described by the Meteorological Office (Great Britain) ([20]) in which a small tungsten filament searchlight is used with a simple receptor having a photovoltaic cell and optical shielding. A small photocell on the front glass of the searchlight is used to monitor the light source; the indications of the cells are read on a taut-suspension galvanometer. This is suitable for ranges up to about 1,000 ft.

Rey and Févrot ([19]) describe a slightly different method, in which the total flux in the beam of a very narrow angle projector is measured. The projector consists of a very small tungsten filament lamp at the focus of a precise lens, 18-cm. diameter, very accurately set and focused. The whole beam, which is only about 25-cm. diameter at a range of 300 m., is received on a mirror which is one quarter of a large searchlight mirror having its focus offset, and is focused upon a receptor consisting of a ground glass window with a photocell a few inches behind it. For calibration the whole receptor is transported to a position near the projector.

Any permanent transmissometer installation calls for rigid and precise mounting of the components, and great care to ensure the maintenance of the intensity of the standard projector presented to the receptor.

Collier ([13]) has described a number of visual telephotometers and discussed the principles involved in their design and use. For the measurement of the apparent intensity of a distant light, instruments of the Maxwellian view or stellar types have the advantage that they can be used with lamps of comparatively low power and do not require standard projectors; this avoids the difficulties of accurate mounting and maintenance of a projector. The calibration of these instruments may involve the provision of a second very small light source of known intensity close to the instrument.

The second method, involving the measurement of the brightness of a distant

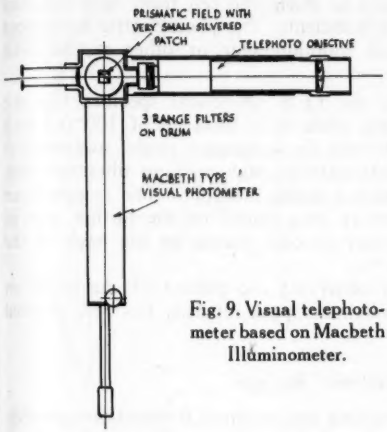
PRISMATIC FIELD WITH VERY SMALL SILVERED PATCH
TELEPHOTO OBJECTIVE
3 RANGE FILTERS ON DRUM
MACBETH TYPE VISUAL PHOTOMETER

Fig. 9. Visual telephotometer based on Macbeth Illuminometer.

illuminated screen, is simpler for visual photometry at medium ranges (say up to 1,000 ft.) and for temporary work. The telephotometer can be sometimes adapted from an existing illuminometer and the distant illuminated screen is not necessarily inconveniently large. The instrument may take the form of a telescope having a small prismatic field at its focus; with this form the angular field may be very small, which permits the use of a small target. Collier [13] has described several instruments of this form. A portable instrument has been used [16] having a 1-in. diameter telephoto lens with an equivalent focal length of 21 in. attached to an instrument of the Macbeth type (Fig. 9). A very small prismatic field was used. The target consisted of a 30-in. copper hemisphere painted white inside and illuminated by a small opal lamp at its centre; this gives a very nearly uniform brightness and is easily portable. This arrangement works well at ranges up to 1,000 ft. Benford has described instruments intended to work over ranges of 2,300 ft. and 3 miles, the smaller having an objective of 6-in. diameter and 18-ft. focus and the latter an objective of 15-in. diameter and 30-ft. focus [1].

Telephotometers suitable for measurements over testing ranges are not commercially available and have generally been designed and made for particular ranges.

(3.6) Telephones

Telephone communication between the projector operator and the observer at the distant station is essential; it has been found useful for one or both to be provided with headsets so that they can converse while making adjustment. Loud-speaking telephones of the inter-office type are also convenient on permanent installations [23]. Reliable equipment properly installed is necessary, range telephones are proverbially exasperating and can waste much time and temper on an important experiment.

(4) Photometry Over Short Ranges

The photometry of small projectors can be carried out over ranges of 100 ft. or less, at which many of the problems discussed above vanish. The range can be indoors, which can eliminate the troubles due to stray daylight, and atmospheric problems are usually negligible—though in foggy weather, or in a dusty building, surprisingly large errors can occur. The photometric procedure then becomes much simpler. A turntable is still required, though there are many standard laboratory equipments which are suitable. Angles may be measured on less elaborate circles; the method using the telescope or projector is, however, often very handy, particularly when rather elaborate explorations are involved. It is particularly convenient to bring the leads from the photocell back to the projector, so that the experiment can be concentrated at one end of the range. This is safe with photovoltaic cells at short ranges of 50-100 ft. If it is inconvenient to rotate the projector, the beam may be formed on a screen and explored by a movable photocell or a visual photometer. If a flash camera is used, a mirror can be placed at the receptor so that the camera can be used alongside the projector—a great convenience in focusing and adjusting. A high quality plane mirror is required, of a diameter exceeding one-half of that of

the projector aperture. It is usually necessary to shield the cell from light reflected from walls, etc., but a simple shielding box is sufficient. The photoelectric equipment may be calibrated by reference to a visual illuminometer or other standardised instrument.

For the testing of floodlight projectors, the I.E.S. (America) specifies that the intensity shall be derived from measurements made at a distance of 100 ft., each determination being made with a receptor having an acceptance angle, measured at the projector, of 1 square degree. This avoids spurious high readings obtained from some chance striation which does not represent a useful intensity. The receptor can conveniently take the form of a square aperture in a shield, on the farther side of which is an integrating hemisphere. A number of cells placed on the back of the shield receive light from the hemisphere ([25, 26]).

Focusing is conveniently carried out by observing the pattern of the beam on a screen, though a check to ensure that the maximum peak intensity has been secured is advisable.

(5) Optical Photometric Ranges

For approximate work, and for works checking and setting it is sometimes possible to compress a long photometric range into a few feet, by the use of optical methods analogous to the optical shielding already described. For a receptor a large paraboloidal mirror of high quality is required, such as a selected searchlight mirror large enough to accept the whole of the beam tested. A pinhole stop is placed at its principal focus; the only light which can pass through the pinhole after reflection at the mirror is light which was incident on the mirror very nearly parallel to its axis (Fig. 10). This light can be used to form a flash image of the projector projecting light on to the mirror, or it can be passed to a photocell to measure the intensity of the projector ([31]). This method is valid only for approximate measurements and when the precision of the collector mirror is appreciably better than that of the optical system under test, but it is useful for a works test of production equipment, and for setting up.

(6) Determination of Beam Flux

The total flux in a beam of projected light may be obtained by integration of the intensity distribution, if this has been measured in sufficient detail. It is desirable that a complete isocandle distribution should be known, not merely the candlepower distribution in two principal planes at right angles.

A device similar to the optical photometric range has been employed to measure directly the total light flux in a projected beam ([5]) in which the projected beam is received on a collector mirror and is concentrated on to a water-cooled white surface. This surface forms a secondary source, from which the total light flux can be obtained. It is calibrated by reference to beams the flux in which can be calculated from complete intensity measurements. A simpler method for determining the total flux in a beam is to allow the beam to impinge on a large white screen and to use the screen as a secondary source to illuminate a test plate or cell. The flux can be calculated if the reflection factor of the screen and its distance from the test-plate are known, and if it is a good diffuser ([16]).

A more elaborate apparatus for the measurement of beam lumens was devised by Benford ([1]) in the form of a large (110-in.) hemispherical integrator of sufficient aperture to receive the whole beam. The aperture of the integrator could, if necessary, be closed by a very large iris diaphragm, when measuring beams of small width. It was found that the integrator paint had characteristics which departed slightly from those of a perfect diffuser, and in order to compensate for errors which resulted, a

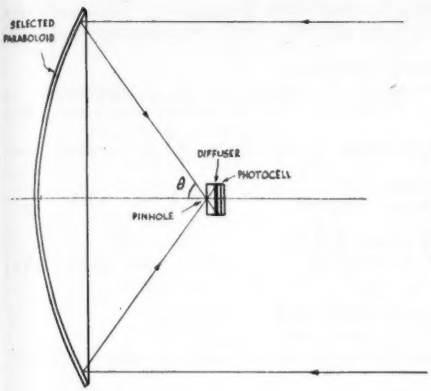

Fig. 10. Optical photometric range.

(NOTE :—This arrangement does not give correct quantitative results because light near the margins of the mirror traverses the pinhole obliquely and suffers a reduction of $\cos\theta$ where θ is angle shown. But it will usefully indicate a maximum when focusing. To get a flash image exchange photocell for a neutral glass about 0.05 transmission (to act as light trap) and view diffuser directly).

series of masking fins was used which obstructed a small proportion of the light reaching the margin of the opening of the hemisphere.

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(27) Engineer Research and Development Laboratories, U.S. Army, Fort Belvoir, Va., U.S.A.
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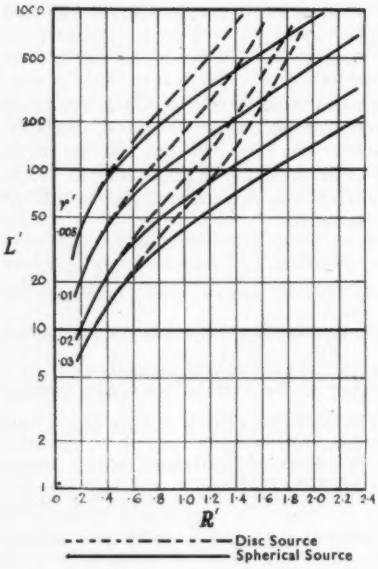

Fig. 11. Crossover point for paraboloid mirror (on axis) (Hampton)

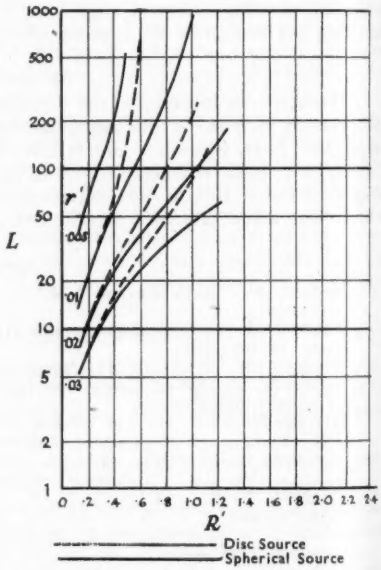

Fig. 12. Crossover point for dioptric system (on axis) (Hampton)

Appendix

Distance of Crossover Point for Projection Equipment

The distance of the "Crossover Point" had been calculated by various investigators for equipment of various types, for sources idealised to either the sphere or the disc, and for axial or oblique directions. The distances are given by Hampton (11) for axial intensity for parabolic mirrors and for dioptric lenses, and for either spherical or disc

sources, by the following formulae, which are of the same forms as those derived by other works; he has plotted the results in graphical form as given in Figs. 11 and 12.

Axial Intensity

(1) PARABOLOIDAL MIRRORS

(a) *Spherical Source*

$$L' = R'/r'.\ (1 + \tfrac{1}{4}R'^2)$$

(b) *Disc Source*

$$L' = R'/r'.\ \frac{(1 + \tfrac{1}{4}R'^2)}{(1 - \tfrac{1}{4}R'^2)}$$

where R' = Radius of edge of mirror
r' = Radius of source
L' = Distance of crossover point from mirror edge
all expressed as multiples of focal length.

(2) DIOPTRIC APPARATUS

(a) *Spherical Source*

$$L' = \tan\theta/(r'\zeta\cos\theta - \eta\delta_{nR})$$

(b) *Disc Source*

$$L' = \tan\theta/(r'\zeta\cos^2\theta - \eta\delta_{nR})$$

where R', L' and r' are as before:

θ is maximum angle to horizontal subtended by the extreme element;

δ_{nR} is chromatic dispersion for red light measured from the wavelength for which the lens was designed (= 0.004 for Lighthouse Crown glass).

n is refractive index

$$\delta \text{ is } \frac{-\cos\theta\,(n^2 - \sqrt{n^2 - \sin^2\theta})}{n^2 - \sin^2\theta - \sqrt{n^2 - \sin^2\theta}}$$

$$\eta \text{ is } \frac{n\sin\theta}{n^2 - \sin^2\theta - \sqrt{n^2 - \sin^2\theta}}$$

For axial measurements, Walsh gives the approximate rule:—

$$L' = R'/r'$$

so long as the source of light is small.

Off-Axis Intensity

For points off the axis the theory is more complex, and is discussed in detail by Benford [1] and by Walsh [2] whose papers should be consulted for cases in which refined measurements are concerned. Hampton has discussed [6, 11] the theory of the dioptric lens.

For inclined directions with a paraboloidal mirror Walsh gives the equation:

$$R/L = \frac{r(f - R^2/4f)}{(f - R^2/4f)^2} - \theta$$

where R, r and L are the above quantities in absolute units and f is the focal length,
and θ is the angle from the axis at which measurements are to be made.

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